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Additive Layered Manufacturing: Sectors of industrial application shown through case studies

Abstract. In modern industry, mass production has migrated to third world countries. To be competitive, European companies are forced to rapidly switch towards manufacturing of short series of customized products with added value. In European industry, a great effort has been made in order to customize products and give them an added value by developing new fabrication technologies. Additive Layered Manufacturing (ALM), also known as Rapid Manufacturing (RM), is a powerful tool that offers the necessary competitiveness to European companies. ALM comprises the use of layer-by-layer manufacturing in order to build a part by addition of material. Fabrication is performed directly from the 3-D CAD model, which is sliced into layers that are printed one upon the other. Also known as Free Form Fabrication, Additive Fabrication 'unlocks' design potential since part design obeys functionality, pushing the limits of manufacturability. In this paper, the authors review ALM technologies and the state-of-the-art of ALM applications in tooling, biomedicine and lightweight structures for the automotive and aerospace sectors. The authors present their experience in industrial application of Additive Fabrication through various industrial technology transfer projects made to transfer ALM technology to SMEs. Various case studies are presented and the achieved benefits of ALM are shown.

Keywords: additive layered manufacturing, customized product

1. Introduction.

In recent years, European industry has been facing the challenge of losing competitiveness in mass production. Due to important factors such as lower labour costs, lower taxes or in-site access to raw materials, mass production has migrated to third world countries. However, European industry is more advanced in technological aspects and is in need of a qualitative advantage in the development of new technologies. One of the efforts of European companies is directed towards the production of short series of customized products with added value. A great effort has been done in order to customize products and give them an added value by developing new fabrication technologies. Additive Fabrication (AF) is a powerful tool that offers the necessary competitiveness to European companies.

There are many terms commonly used for AF, such as Solid Free Form Fabrication (SFF), Rapid Manufacturing (RM), Additive Layered Manufacturing (ALM) and 3D Printing (3DP). The latter may be the most descriptive for those not familiar with additive technologies. Unfortunately, this term may produce a wrong idea, since AF machinery is much more than any kind of printer. Anyhow, AF comprises the use of layer-by-layer manufacturing in order to build a part by addition of material.

1.1. The physical process of addition

Additive fabrication is performed directly from a 3-D CAD file in which a part's model is stored. The usual file format is STL. The STL file is imported into a specific software (such as Magics RP[®] by Materialise, Viscam[®] by Marcam and Netfabb[®] by FIT which are available in the market), where it is pre-processed. The part is oriented for building and a support structure is made for the part's surfaces that are facing down. Afterwards, cross-sections of a given thickness, known as 'slices', are generated from 3-D CAD descriptions of the part and support structures. The slices are saved in a 'slice file' (SLI, SLC or any other format that may depend on patented technology). After pre-processing, the slice file is sent to the machine to be 'printed' slice-by-slice.

Insert Figure 1 about here

The fabrication process consists of two basic steps: *coating* and *fusing*. The *coating* step is the process in which material is laid over the working surface forming a very thin layer. The thickness of the layer depends on the chosen technology and is in the range of 0.03 mm to 0.20 mm. The *fusing* step refers to the process of printing the part slice by the action of a source of energy. The active principle can be a *light source*, *laser beam* or *electron beam*. It acts over the layer of material and produces fusion, which fuses the part slice's footprint to the layer below it (Figure 1). The power of the source of energy depends on the chosen technology: in the low end, we have Stereolithography that uses 100 W, and in the high end, we have Electron Beam Melting that uses 3000 W. Only the contour of a part slice and its interior are fused; the rest of the material is left untouched and may be recycled (depending on the process and material). The actions of coating and slice printing follow each other until all the slices are printed correctly, forming the final three-dimensional part. Once fabrication is finished, the part is taken out to be cleaned of material that is not fused and, if necessary, to be given further post-processing. The most common post-processing techniques are sanding, polishing, homogenization, thermal treatment, etc.

It is important to note that, in general, material that is not fused (be it powder or liquid) is not capable of supporting fused structures. If a part has overhanging zones, they may need to be supported by a firm structure. Additionally, the support structure acts as a conductor of excess heat created in the process of fusing. Finally, in some technologies, the support structure prevents warping of the part due to the thermal stress created during the process. Hence, the first step of pre-processing actually consists of generating an efficient support structure, which is then sliced and fabricated together with the part.

1.2. Advantages and challenges of AF

The most important advantages of Additive Fabrication are:

1. *Time-to-market reduction due to high speed of the process.* A complex race car upright (Figure 2) whose dimensions are 280 mm x 180 mm x 120 mm was designed and fabricated by EBM in just 28 hours (Arcam (2006));

Insert Figure 2 about here

2. *Product customization with complete flexibility in design & construction of a product.* Unlike conventional processes, AF can produce parts of almost any desired form and can almost be free from geometrical manufacturing constraints.
3. *Maximum material savings.* Material is added and not subtracted. For some applications, especially in the metal sector, case studies show that the waste of raw material is reduced by up to 40% when using additive technologies instead of subtractive (machining) technologies (Reeves (2008)). Also, 95% to 98% of the remaining material (powder that is not fused) may be recycled;
4. *No tools, moulds or punches are needed.* The part is obtained directly from its 3-D CAD model; an additional advantage is the almost absolute absence of human errors in production.
5. *Full-density of final parts.* Unlike other powder-bed processes, additive technologies produce parts without residual porosity.
6. *Fabrication of free form enclosed structures.* Additive technologies are capable of fabricating free form channels as well as different forms of latticed structures.

However, additive technologies must face some pending challenges in the near future.

1. *Remove the 'stigma' of its original name 'Rapid Prototyping'.* Although ALM has evolved in a way that it delivers ready-to-use products made from a wide variety of metals and polymers, it is still wrongly considered that additive fabrication is valid only for prototype fabrication.
2. *Validation of mechanical and thermal properties of existing materials and ALM technologies.* Unlike conventionally produced parts, AF parts do not behave identically in all directions. They are 'stronger' when the load is applied along the direction of the layer as compared to the build-up direction. At the moment no characterization has been done to quantify the difference. Hence, a client will fully trust ALM technologies when the proper part characterization is done.
3. *Development and characterization of new materials for ALM.* Additive technologies are already dealing with a wide variety of metals (stainless steel, titanium, cobalt chromium, etc.) and polymers. However, there are many interesting materials that need further research (such as magnesium, copper, biodegradable polymers, etc.).
4. *Change in the designers' way of thinking.* ALM has enabled a new "free form fabrication" that is free from manufacturing constraints and must be introduced and advertised.
5. *Automation design and process planning.* The overall tendency in production processes (no matter if subtractive, forming or additive) is the development of automatic assessment tools. There are several result parameters that are considered when one designs for AF and all of them can be put together in order to automate decision making in ALM.
6. *The stair stepping effect* is created by the placement of one layer on top of another, affecting surface quality and roughness. Depending on how the model is oriented for slicing and fabrication, roughness will be better or worse in different zones.
7. *Support structure.* As the material used for the support structure cannot be recycled, it should be minimized by a good build-up orientation.

In this paper, the authors review the main AF technologies and their actual industrial applications, offering a global view of the state-of-the-art in additive fabrication. The most relevant and commonly used additive technologies are briefly commented. These technologies are capable of processing a wide variety of materials (polymers and metals). After a brief introduction of all technologies, the most attractive fields of application are highlighted. Finally, the authors describe their experience in the application of additive fabrication in the tooling, biomedicine, aerospace and ceramic industries, underlining the qualitative advantages offered by AF. The Results section shows various case studies in the framework of AIMME's projects related to biomedicine (Fabio), tooling (Heat Transfer Tooling and Custom Ceramic) and lattice structure (Mepess).

2. Additive technologies

2.1. Polymer processing

Polymer processing technologies have been present in the global industry market for almost two decades. These technologies are well known in all industrial sectors because they have been widely used for prototype fabrication. In this section, only the most widely used will be mentioned.

2.1.1. Stereolithography (SLA)

SLA technology uses a laser beam to perform the photopolymerization of a material. This way, the material that is initially in a liquid state becomes hard and consistent. SLA is capable of processing different resins that emulate the performance of thermoplastic material. Actually there are many types of resins that are capable of resisting different loads and temperatures. Some of them are for general purpose and others have been developed for a specific use: high thermal resistance, better surface quality, elasticity, dimensional precision or other.

Both the technology provider (3D Systems) and material providers (such as SOMOS) offer a wide range of materials that are capable of being processed successfully. There are materials made for general purpose use (Somos 7100), for the good emulation of the properties of thermoplastic materials (Somos 8100 and Somos 9100), to provide stiffness and resistance to high temperatures (Somos ProtoTool TM and Somos NanoForm TM) and to provide high precision (3D Systems Accura Amethyst TM or 3dSystems Accura Bluestone TM).

The main application fields for SLA are the construction of functional and aesthetic prototypes, construction of models for VC and models with non-crystalline nanoparticles as mould inserts in the injection of certain polymers.

The main advantages of SLA are the fabrication of very complex geometries, very thin wall features, SLA parts with resistance to high temperatures and high reliability. The main disadvantage of SLA is that the operation of changing from one type of resin to another requires a substantial amount of time.

2.1.2. Selective Laser Sintering (SLS)

This technology uses a laser beam to fuse powder and create a part layer by layer. It normally uses powdered polyamide that can sometimes be reinforced with a filler of glass fibre or aluminium. The main advantages of polyamide are its good mechanical properties and stiffness which make it possible to fabricate a model without the need of a support structure which is generally needed for the downfacing surfaces of the model.

One of the most representative technologies for SLS is provided by Electro Optical Systems. This company has a variety of machines such as Formiga P 100, EOSINT P 390, etc. EOS offers a variety of materials for use in their laser-sintering systems. These materials are based on PA 12 or polystyrene. Polyamide has a good resistance to most chemicals, and the material itself is not critical with regard to environmental and health aspects. There is a wide range of variants of this material to satisfy the special requirements of different applications. These materials can be distinguished, among other things, by the type of filler, for example with aluminium (Alumide), glass or carbon fibre (CarbonMide).

SLS technology is mostly used for prototypes, models and final products. Regarding the technology providers, apart from EOS, 3D Systems (www.3dsystems.com) is also present in the world market. The main advantages of SLS technology are the use of polyamide materials with good mechanical characteristics, the possibility of fabricating parts with up to 30% of glass fibres, the capability of resisting higher temperatures than SLA parts (up to 140°C), good performance at increased levels of humidity, the absence of a support structure and a higher rate of fabrication. The main disadvantages of SLS are porous surfaces, possible warping of the part due to high temperature gradients and dimensional tolerances that are difficult to control.

2.1.3. Digital Light processing (DLP)

The technology known as DLP uses a UV-light lamp to expose a photo-sensible resin which will solidify. The Perfactory Xede and Xtreme machines use DLP-based projectors patented by Texas Instruments to produce multiple parts in a continuous Z build mode. This technology allows for the production of highly accurate parts without the trade-off between precision and building speed.

There are different variants in materials that can be used on DLP machines. The most commonly used are R5 and R11 for high-precision models, PIC 100 and 100G for jewellery and vacuum casting models, and the E-Shell 100 and 200 biocompatible materials for external use.

The main advantages of DLP technology are the fabrication of very complex geometries, very thin and precise details, and an excellent surface finish. The main disadvantages of this technology are its limitation to fabricating only relatively small parts and the difficulty of eliminating the support structure without causing damage to the part's surface.

2.1.4. Fused Deposition Modelling (FDM)

FDM technology consists of the deposition of fused material which was previously stored in the form of a plastic thread on a roll. Materials used in FDM are usually based on polycarbonate (PC) and ABS or a mixture of these two. Known as PC-ABS, PC-ISO or ABSi, these materials have properties that are similar to thermoplastic material for injection moulding. Also, nylon-based materials and other polymers can be used. The main advantage of FDM technology is in the use of low-cost materials.

Regarding available materials, ABS (P400 and P500) is suitable for functional prototype construction. Also, E20 is an elastomeric material available for highly flexible prototypes.

The main advantages of FDM technology are the fabrication of low cost parts, the use of water to dissolve the support structure and the possibility of coating the surface to improve its quality. The main disadvantages are a poor surface quality with grainy appearance and poor dimensional precision.

2.2. Metal processing

The raw material in metal processing with additive technologies is powder (powder bed technologies). The working principle is similar in all technologies and consists of coating and fusing. A thin layer of powder is coated over the working platform and a slice is printed by fusion. The platform descends along the Z-axis an amount equal to the thickness of a slice and a new layer of powder is coated over the working platform so that the next slice may be printed. The actions of coating and slice printing are repeated until all the slices are printed correctly, forming the final part.

The source of energy used for fusion can be of the *laser* (laser based technologies) or *electron beam* (electron beam melting, EBM[®]) types. All metal processing technologies are capable of producing fully-dense and functional parts. These parts are offering complete reliability and are used in many industrial sectors such as biomedical, tooling, aerospace, automotive, etc.

2.2.1. Laser based technologies

In laser based technologies, a focused beam of laser light is used to produce fusion. There are several variants of laser technology. All of these laser technology variants are available in their respective machines. Generally, the parts fabricated with these metal processing technologies are prone to oxidation which can diminish their mechanical properties. This is why laser-based machines work with a protective atmosphere in the build chamber. When working with steel powder, nitrogen is commonly used, while for processing titanium and cobalt-chromium, argon is the best option to create an inert atmosphere.

Selective Laser Melting (SLM) is currently found in two variants, developed respectively by Electro Optical Systems and MTT Technologies. EOSINT M 270 is capable of processing a huge variety of metals such as steel, cobalt chromium, titanium alloys (Ti6Al4V), bronze-based alloys, nickel-based alloys, etc.

MTT machines, SLM 100 and SLM 250 are capable of processing stainless steel, tool steel (H13), titanium alloys (TiAl6V4 and TiAl6Nb7), cobalt chromium, AlSi12Mg, etc.

Another patented laser technology is Laser Cusing, property of Concept Laser. This technology is available on three machines, M1, M2 and M3. While M1 and M3 are capable of processing stainless and tool steel, M2 is capable of processing non ferrous alloys as well, such as titanium (Ti6AlV4), aluminium (AlSi12 and AlSi10Mg) and nickel based alloys.

Also available in the market is Selective Laser Sintering, property of 3D Systems, and a type of Laser Sintering developed by Phoenix Systems.

2.2.2. Electron beam based technology

In electron beam melting, the energy is provided by the impact of a focused beam of electrons. The electrons are emitted from a filament made of tungsten. A series of electromagnetic coils are used to focus and direct the beam towards the working platform. The particularity of EBM technology is its use of a vacuum in the build chamber. The vacuum prevents the beam from being deflected and maintains it well focused. This technological characteristic is wisely used to obtain parts of high purity.

There is only one EBM technology available, it is patented by Arcam and it is available on two machines: Arcam S12 and Arcam A². These machines can process any material that has an adequate electrical conductivity. However, up to the moment, only three types of titanium (Ti6Al4V, Ti6Al4V ELI and Ti Grade 2) and cobalt chromium (CrCo ASTM F75) materials are officially released for EBM.

3. Application sectors

Additive fabrication is able to offer an added value to products and increase their quality as can be seen in the following section.

3.1. Polymer parts

3.1.1. Prototypes

The original purpose of SLA and DLP parts was to use them as prototypes for visual validation and validation of assemblies. There is a large number of applications for polymer prototypes. Some of them can be shown on Figure 3.

Insert Figure 3 about here

3.1.2. Biomedical parts

Polymer materials are very important for the biomedical sector. There are three different types of polymers that can be used in the biomedical sector. These are biocompatible polymers for external use, biocompatible polymers for implants and biodegradable polymers for implants as well.

Biocompatible polymers for external use are those that can be used for medical or prosthetic devices. An example is the EnvisionTEC e-Shell 200 series material that has been designed specially for applications in the Hearing Aid industries and is distinguished for its rigidity and durability. It is suitable for thin-walled Hearing Aid shells and otoplastic products. The material is used on all Perfactory[®] and Vanquish[®] systems. An example is shown at Figure 4(a).

Biocompatible polymer materials have been used in the surgical implants industry. These materials are not aggressive to the human body and do not cause rejection. Figure 4(b) shows a coronary bypass implant with very small internal channels. This model was fabricated with the photopolymer R11 material. Additionally, guides for maxillofacial surgery have been fabricated with transparent photopolymers.

Insert Figure 4 about here

Hard tissue lumbar implants made with Stereolithography for vertebral fixation have been implanted on cadavers and used in clinical studies (Goffin (2001)). Also, various research works have been conducted to obtain scaffolds for tissue engineering using polylactic glycolic acid (PLGA) and fibrin gel (Liu (2008)) or a combination of ether, epoxy resin and a photoinitiator (Quadrani (2005)).

The next step in implant fabrication is the use of *biodegradable* polymer materials. Implants with the most desired features in implant research would have structures that have an osteoinductive function that permits bone growth and would also degrade with time. Additionally, flexible forms of these polymers would permit real tissue engineering, being a base for the construction of human organs.

3.1.3. Artistic design

Due to its extraordinary capacity of obtaining free forms, AF is frequently used in artistic design. Parts such as the one shown in Figure 5(a) can only be fabricated by additive technologies. One of the special fields in which additive manufacturing has been used is jewellery design. Unique designs become a reality with polymer processing. Polymer models can serve as models for vacuum investment casting (Figure 5(b)) or they can serve as jewels themselves (Figure 5(c)).

Insert Figure 5 about here

3.2. Metal parts

3.2.1. Tooling

The tooling sector has already been converted into a stronghold of AF. Additive technologies offer the possibility of free form design. One of the principal tasks in mould making is to provide adequate cooling. Post-injection warping and contraction of parts, as well as overall quality, are strongly influenced by the heat transfer between the injected mass and the cooling liquid that flows through the mould's walls. Cooling channels are normally obtained by drilling, once the mould has been machined. Hence, in conventional mould fabrication, the cooling channels are normally straight (Figure 6(a)).

Insert Figure 6 about here

Additive technologies enable the fabrication of *free form cooling channels*. These channels are designed to follow the mould cavity surface and provide a completely homogeneous heat transfer, *adaptive cooling*, which helps to provide better quality to injected parts. Another important issue is the *injection cycle time* since adaptive cooling enables significant reduction of cycle time.

Metal additive technologies, laser or electron beam-based, are capable of fabricating hybrid moulds. In other words, they can build mould inserts over pre-fabricated mould blocks. Hence, only the mould cavity zone is fabricated by AF, saving time & costs comparing with full mould fabrication by AF (Figure 6(b)).

There are many research works that support this claim. Godec (2008) emphasize an experimental comparative analysis of the influence of hybrid and classic moulds on the properties of moulded parts and their processing parameters, showing the advantages of tool inserts made with DMLS. Wong (2007) conducted a study that demonstrates the

1
2 performance enhancements that can be achieved by using novel heat sink designs, fabricated with Selective Laser
3 Melting, as compared to conventional pin fin arrays. Rännar (2007) shows that efficient mould inserts with conformal
4 cooling channels can be fabricated with EBM.

5 Although this subsection deals with metal parts, when speaking about Rapid Tooling, a use of Stereolithography in
6 mould inserts fabrication must be mentioned. Silica moulds for aluminium casting have been successfully used
7 (Esposito (2006)), and SLA has been used to fabricate PEK mould inserts (Harris (2004)).

8 3.2.2. Biomedical parts

9 The main field of application for additive technologies may be resumed in the following statement: *customized parts*
10 *with short fabrication series*. Biomedical parts are the target group that fits perfectly into this definition. Implants are
11 highly personalized and as unique as the human body. The advantages of AF in biomedical applications are numerous.
12 The most important can be summarized as follows:
13

- 14 • *Complex and personalized forms can be obtained*: the human body, especially its osseous structure, has a very
15 complex shape full of details. AF is the best option to reproduce these forms.
- 16 • *The overall product development is much faster than conventional processes*: a CT scan of a zone to be
17 reconstructed is accomplished and converted to a model. The model is then exported to a STL file, sliced and
18 sent to the machine: the part is fabricated. Figure 7 shows the overall scheme of the ‘scan-to-part’ process.
19 Apart from being faster, this product development process is automated and the possibility of human error is
20 considerably reduced.
21

22
23 Insert Figure 7 about here

- 24 • *Surgical intervention time is reduced*: a CT scan of the zone to be reconstructed is used also to reconstruct the
25 whole zone, not only the implant. A polymer model of the surrounding zone where the implant must fit is
26 fabricated with AF (normally with Stereolithography). This way, all the necessary adjustments of the implant
27 can be made using the model, *before the surgery begins*, which avoids the risk of having more than one
28 surgical intervention. This is essential for the post-operative period since the patient will recover in a shorter
29 time.
30

31
32 Insert Figure 8 about here

- 33 • *Gradual structures can be fabricated easily with AF*. Both the exterior and interior of an implant can be
34 fabricated employing a lattice structure (Figure 8). The option of having a fully-dense core and a gradually
35 formed lattice structure towards the exterior is favourable for *osteoiduction, osteoconduction and*
36 *osteointegration*. The bone grows “inside” the implant, which is then integrated completely into the body’s
37 osseous structure. On the other hand, an implant fabricated as an external shell with an interior lightweight
38 structure is *much lighter and offers the same strength in use*.

39 Due to these unquestionable advantages, the fabrication of implants with additive technologies is emerging rapidly. It
40 can be predicted that in the near future AF will occupy a major share of the implant fabrication market. However, since
41 it is considered a novel technique, it is submitted to thorough processes of testing and certification. A first step on this
42 road is the use of *customized implants* upon the approval of the surgeon and acceptance of the patient. The pre-clinical
43 and clinical tests are performed before the customized implants are fabricated and implanted. There have been several
44 successful interventions placing implants, made with AF, into the human body (Arcam (2007)).

45 However, some implants are suitable for *serial production*. Before they can be placed on the market, the fabrication
46 process must be certified. In Spain, the fabrication of implants must be done according to Royal Decree RD 414/96,
47 which regulates the fabrication of all sanitary products. The certification includes traceability of raw materials and the
48 certification of the production process. Regarding the first aspect, all technology providers have already completed the
49 process of standardization and certification of the raw materials that they provide together with their machines.
50 However, the second part of the certification is left to the medical device manufacturer who will actually produce the
51 implants. Several steps must be completed in order to get certified for implant fabrication. Anyhow, there are already
52 enterprises which have completed this process such as Adler Ortho for an acetabular cup (Cremascoli (2008)) and
53 Leader Italy for dental implants (Traini (2008)).

54 3.2.3. Lightweight structures in aerospace and automotive parts

55 One of the main target sectors for AF is the fabrication of *lattice or spatial structures*. The idea of having a shell of a
56 defined thickness with a lattice structure in its interior in order to reduce its weight is not new. However, with
57 conventional processes it is difficult to fabricate this structure. Additive technologies enable direct fabrication of lattice
58 structures with gradual and controlled porosity.
59

60 Weight reduction and the increase of the strength-to-weight ratio are important in many industrial sectors. One of the
sectors where weight reduction can be very beneficial is the aerospace industry. Aerospace parts are very expensive
because conventional processes are highly wasteful in their operations. Using AF in the aerospace sector, parts are

redesigned and their weight is reduced, which means that the costs of fabrication will decrease significantly. Also, a lower weight of aerospace structural parts has repercussions on fuel consumption which decreases significantly as well. The advantages offered by AF may be summarized as follows:

- it reduces the use of raw material;
- it reduces buy-to-fly ratios;
- it provides freedom from geometrical constraints;
- it reduces the use of energy.

Some empirical studies (Reeves (2008)) compare traditional manufacturing processes for aerospace and automotive parts (gravity die casting, cross drilling, electrochemical deburring and hole blanking) with Selective Laser Melting. It was shown that the same part, redesigned for Selective Laser Melting, had the same mechanical properties and 40% less material. When the lightweight parts are introduced into aircrafts and vehicles, a lot of energy is saved by using less material in part fabrication and the lower fuel consumption in the useful life of the vehicle. The cited study shows that the overall effect of saving 100 kg in material is 4.3 M€ per aircraft and 770€ per car. Here, both lower price of the vehicle and lower consumption during its useful life is considered.

4. Results and conclusions.

AIMME is an institute that is constantly trying to convert research efforts into industrial applications. ALM technologies and applications are brought to SME users and the advantages of ALM are converted to reality by specific industrial case studies. In the Results section, the authors discuss several case studies deriving from various industrial projects for tooling (HTT, Custom Cooling), biomedical (FABIO) and lightweight structures (MEPESS) applications. These results make obvious the previously mentioned advantages of ALM technologies.

4.1. Conformal Cooling in mould fabrication (Cooling Casting¹, HTT)²

One of the strongholds of AF is mould construction. The possibility of building free-form channels offers an important added value to injection moulds. The HTT and Cooling Casting projects were conceived to respond to the tooling sector's demands and make the most of the main advantages in adaptive cooling: *cycle time reduction and part quality improvement*.

The Cooling Casting project was developed with the goal of improving heat transfer in non-ferrous alloy (ZAMAK) injection moulds and reducing their cooling time so as to improve productivity. This was done by using hybrid moulds consisting of a machined mould block and mould inserts made with Laser CUSING which contain the adaptive cooling channels (Figure 9).

Insert Figure 9 about here

In this project two production cycles were compared: one cycle included conformal cooling and the other cycle did not. The production cycle that did not include conformal cooling resulted in a cycle time of 6.7 seconds, whereas the cycle that included conformal cooling inserts resulted in a cycle time of 5 seconds. This reduction of 1.7 seconds in cycle time translates into an improvement of 180 parts per hour which represents a 33% increase in productivity.

The HTT project was developed with the goal of improving the quality of die-casting parts and eliminating defects caused by bad cooling. Parts were made of aluminium and, due to their particular design, had pores in the zone shown in Figure 10(a). These defects were caused by bad cooling and damaged the quality of the part.

Insert Figure 10 about here

The male and female parts of the mould were redesigned to include conformal cooling channels (shown in Figure 10(d)) as well as an interior honeycomb structure employed to reduce the use of material in the fabrication of the mould (Figure 10(c)). The redesigned male and female parts are shown in Figure 10(e). Thanks to the use of the shell and structure concept in the fabrication of the mould there was a 34% and 33% reduction in the quantity of material required to fabricate the male and female parts, respectively. The final cost of tool inserts was 1800 € and 1700 €, respectively. Also, the simulation shows that the cycle time was reduced by 18% which means that the productivity was increased. Finally, and maybe the most important, the part defects were eliminated due to homogeneous cooling.

4.2. Development of a new generation of biomedical materials and implants (FABIO)³

This project included improvements and applications of new bio-materials and AF technologies to obtain a new generation of innovative customized health products (orthosis, osseous substitutes and prosthesis). The project involved three main lines of investigation (shown in three study cases):

¹ Financed by European Regional Development Fund

² Financed by Spanish Government's Ministry of Industry, Tourism and Commerce

³ Financed by Spanish Government's Ministry of Industry, Tourism and Commerce

- Trans-tibial prosthesis and ankle/foot orthosis (AFO): Development of a new design process for a new generation of “scan-to-part” biomedical products, being able to obtain complex shapes and personalized forms. Definition of the procedure for the integration of several stages of the value chain for customized health products to minimize cost and delivery time.
- Mandible implant: Improvement of polymers for the direct fabrication of biomedical products using additive technologies. The goal is to match, as closely as possible, the mechanical properties of natural bone material (biomimetic properties) by improving the material. Similarly, another goal is to match, as closely as possible, the thermal properties of natural bone material (biomimetic properties) through a new design concept.
- Hip prosthesis: Incorporation of a new design procedure that is capable of generating added value for product design. Generation of 3D structures from AF technologies to obtain controlled-porosity scaffolds.

Figure 11 shows an example, which is actually used by a patient, of a customized socket of a trans-tibial prosthesis made with SLA and the Somos 18420 material.

Insert Figure 11 about here

Regarding the development of new materials, a biocompatible material is being developed and has passed the biocompatibility and cytotoxicity tests. The next step in the development of the project will be the fabrication and use in implant surgery of several custom-made implants (mandible, cranial, etc.) fabricated with the newly developed biocompatible material. Figure 12 shows a part of a mandible that was reconstructed and fabricated with the Envision DLP machine and the newly developed biocompatible material.

Insert Figure 12 about here

4.3. *Selective Space Structures in Rapid manufacturing of ferrous and non-ferrous parts (MEPESS)⁴*

This project has been defined so as to integrate knowledge of selective space structures (SSS) and Additive Fabrication applications so as to produce complex and high value-added ferrous and non-ferrous parts. The idea is to offer a feasible solution to the fabrication of lightweight structures (especially in the aerospace and biomedical sectors) as well as to improve the performance of products intended to support dynamic loads by incorporating SSS.

For this purpose, different types of structures have been analyzed and used to create the interior structure of a part. Regarding their structural behaviour, the selected parts can be divided into two groups. The first group includes parts that are redesigned using SSS in order to improve their strength to weight ratio. The second group includes parts that are redesigned using special dynamic-cell SSS which enables the transmission of movement or displacement.

Working with structured parts is complicated due to excessively large size of their CAD models. Conventional 3D modellers have difficulties managing these files. Hence, special software is used to create and operate SSS parts. The development of this project will require the used of Netfabb by Fruth Innovative Technologies GmbH.

Actual results of this project include a test of the capacity of different technologies to fabricate SSS parts. Some of these parts are shown in the following figures. Figure 13 shows the types of structures accomplished by fabrication with Laser CUSING. These structures are meant to be used in scaffold cooling and weight reduction of automotive and aerospace parts. Figure 14 shows a free form SSS structure made with EBM technology with a pore size of 500 μm (this image was obtained from a Starret HB-350 profile projector). Such a fine structure is desirable in osteoconductive implant structures. As can be seen in the figure, this structure is completely regular and controlled, and has a smooth cell transition. Finally, Figure 15 shows one of the first demonstrators fabricated with EBM: a solid femur bone with a SSS zone.

Insert Figure 13 about here

Insert Figure 14 about here

Insert Figure 15 about here

4.4. *Conclusions*

Additive Layered Manufacturing is a set of emerging technologies that are becoming a serious competitor to machining and forming technologies. Due to their obvious advantages in product customization, maximum material savings, and gradual and controlled porous structures, additive technologies are becoming more interesting to many industrial sectors such as biomedical, aerospace, automotive and tooling. With the introduction of new materials and active principles, the ALM technologies that originally were only used for prototypes and models have now been converted into technologies that can fabricate fully-dense functional parts with high added value, as shown in the previous figures.

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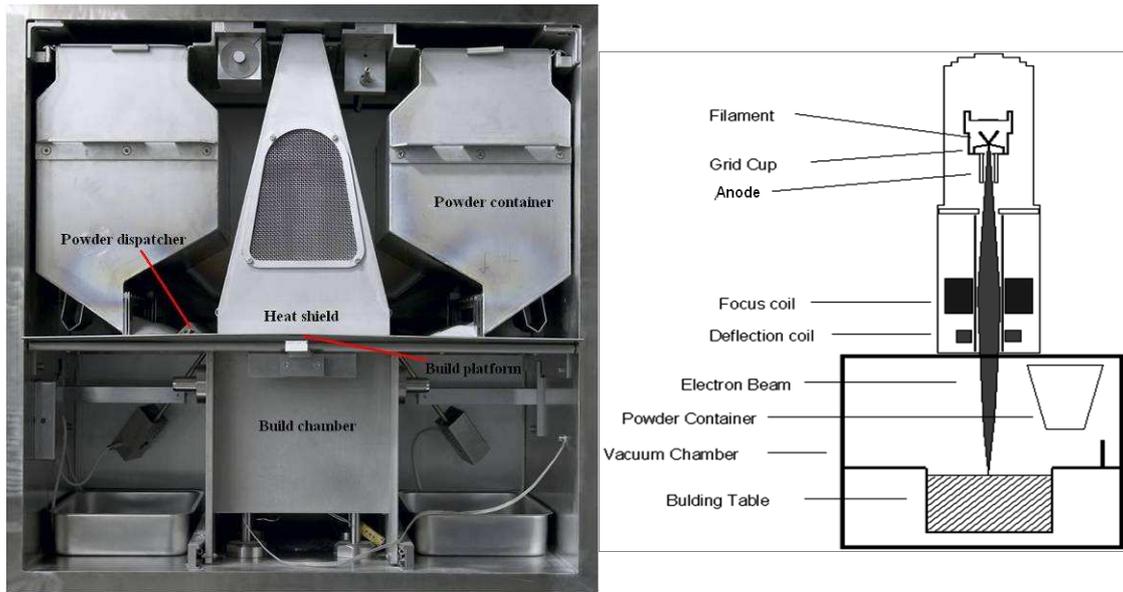


Figure 1. Fusing on an EBM machine (a); scheme of an additive machine (b).

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Figure 2. A race car upright fabricated with Additive Manufacturing (courtesy of Arcam).

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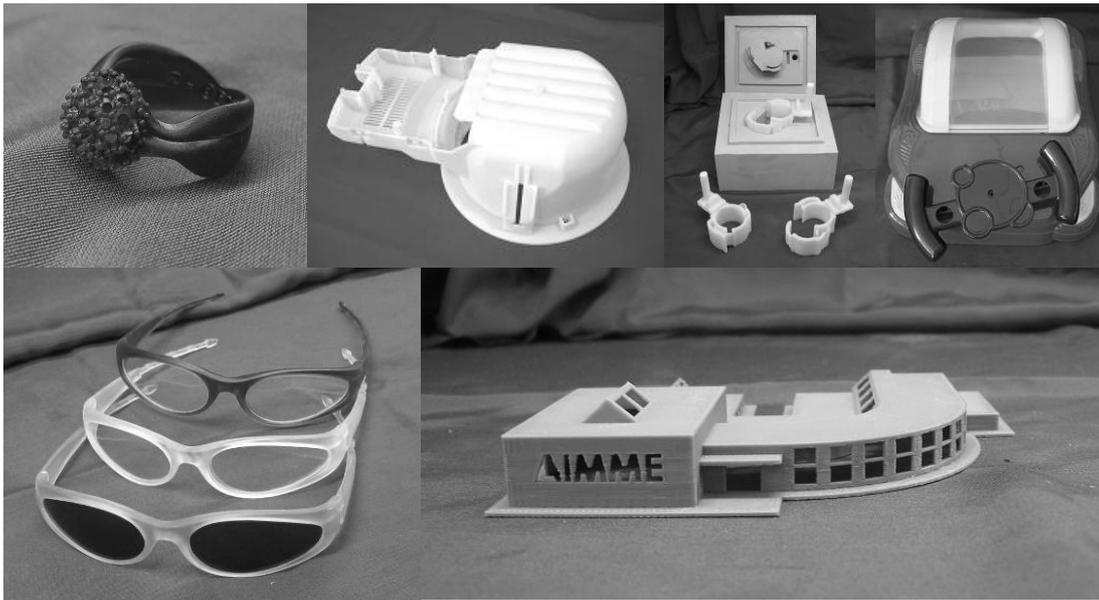


Figure 3. Prototypes and models fabricated with SLA and DLP.

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Figure 4. Hearing Aid apparatus shell (a) and coronary bypass (b).

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Figure 5. Artistic design supported by AF: artistic model (a), jewel model fabricated with DLP and (c) vacuum casted silver ring.

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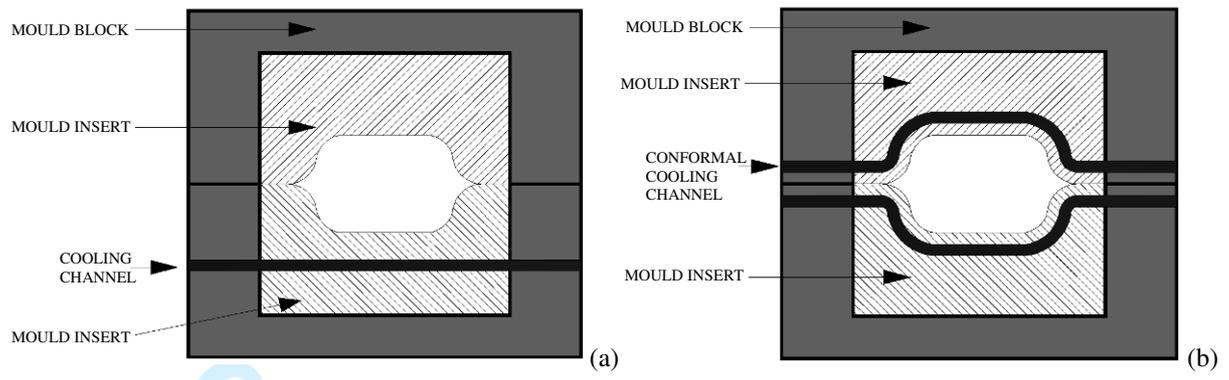


Figure 6. Conventional (a) and conformal (b) cooling channels.

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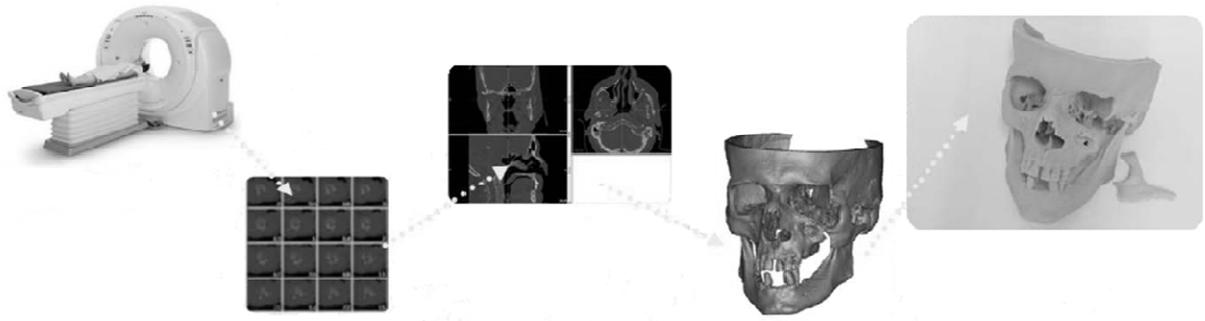


Figure 7. Direct path from CT-scan to part.

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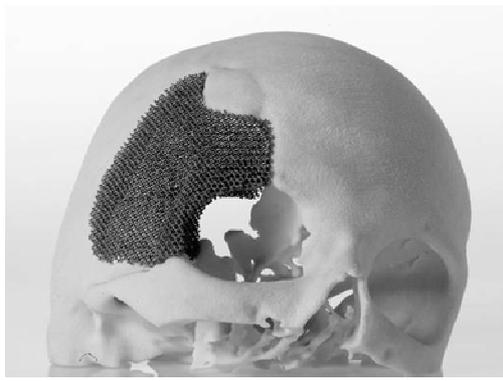


Figure 8. An implant with gradual structure fitted into a model of the zone to be reconstructed.

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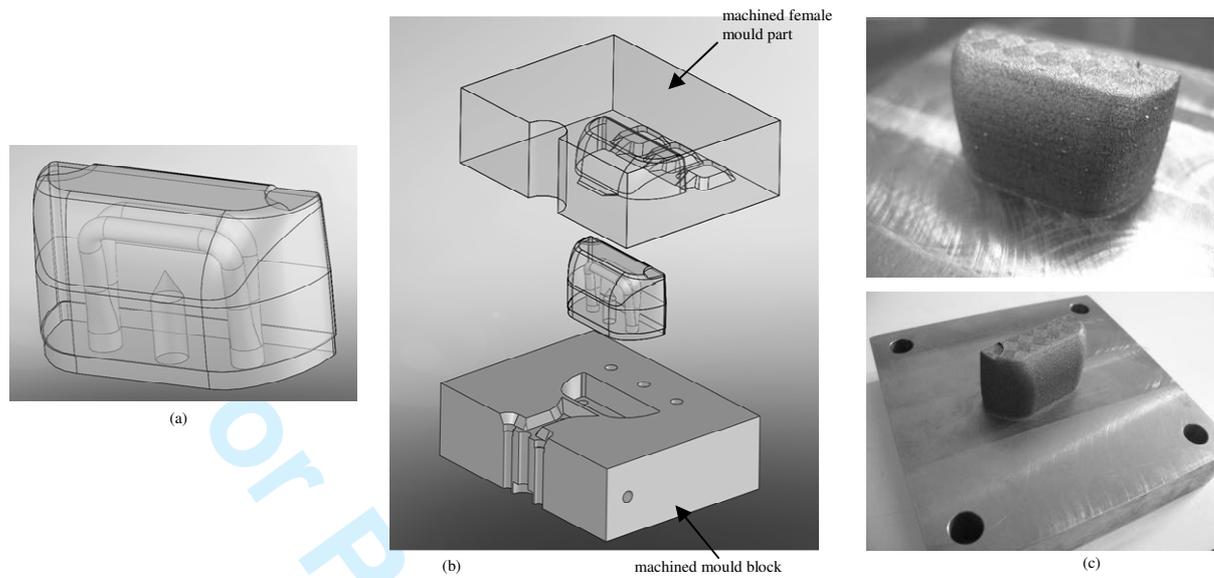


Figure 9. Hybrid mould with free form cooling channels: insert model (a), model of the mould assembly (b) and fabricated and assembled male part of the mould (c).

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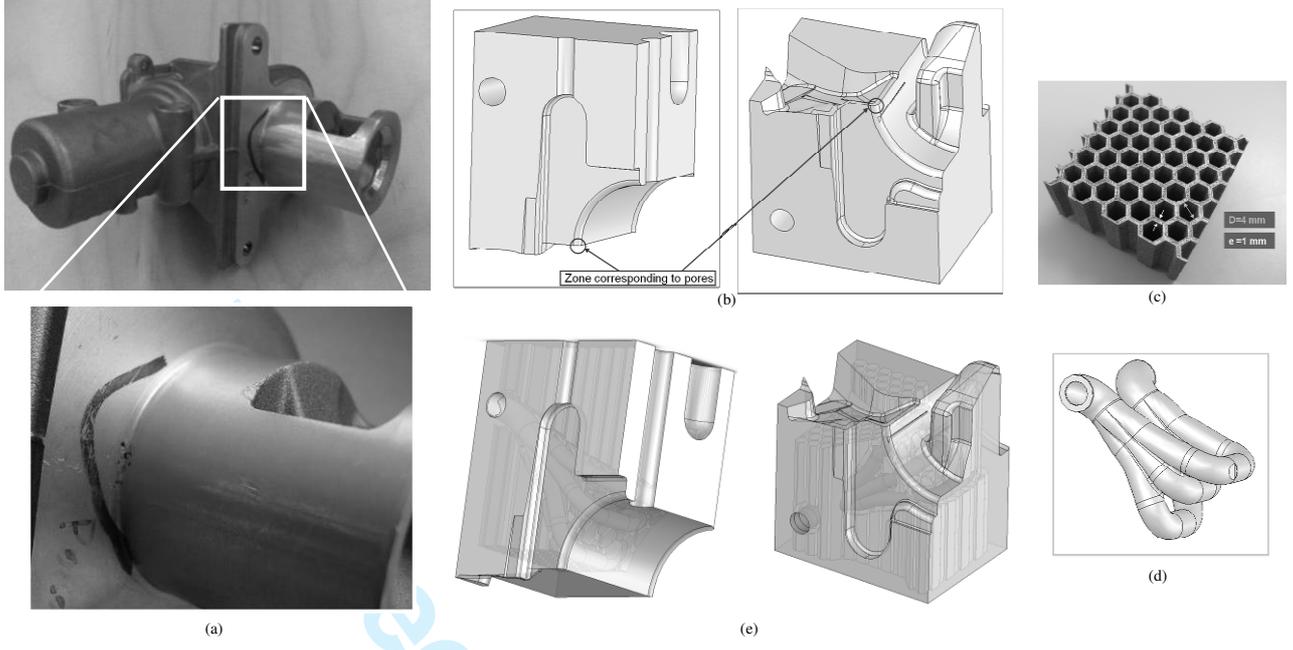


Figure 10. Part quality improvement using free form cooling channels: part defects (a), male and female part of the mould (b), honeycomb interior structure (c), conformal channels (d) and redesigned male and female mould parts (e).

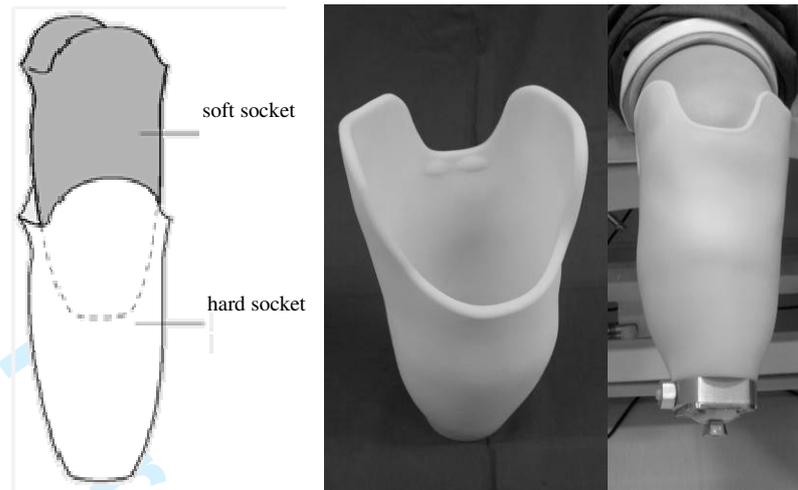


Figure 11. Customized socket of a trans-tibial prosthesis.

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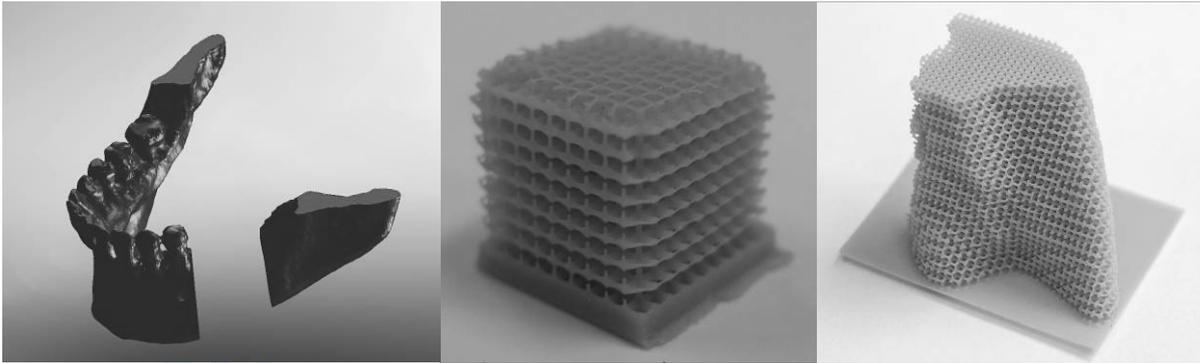


Figure 12. Model of a mandible obtained by scan-to-part (a), the space structure used to reconstruct the missing part (b) and a mandible part made of developed biocompatible material on a DLP machine (c).

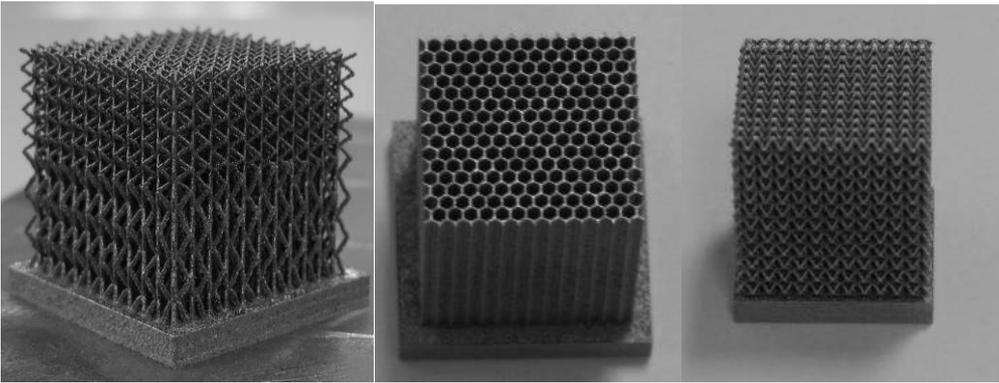


Figure 13. Different types of structures: multi-size cubic cell, honeycomb cell and single-size cubic cell (from left to right) fabricated with Laser CUSING.

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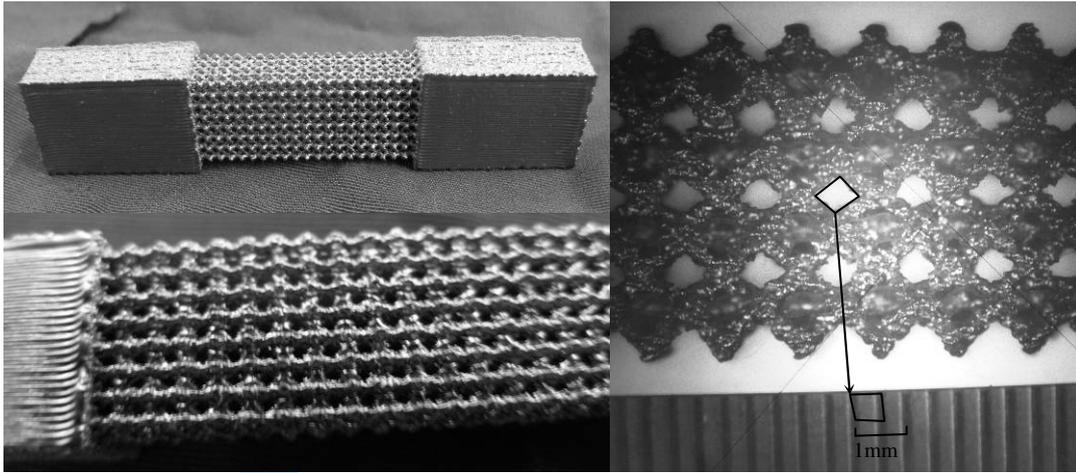


Figure 14. Fine pore space structure fabricated with an EBM machine.

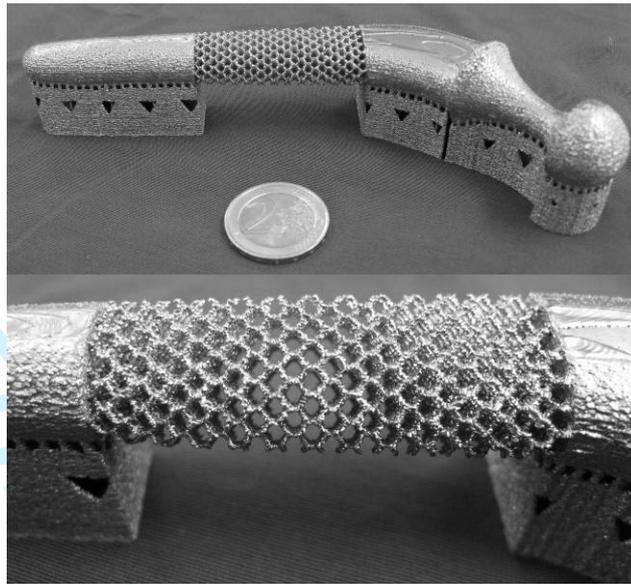


Figure 15. Femur with a SSS zone fabricated with an EBM machine.